UCRL- 92724
PREPRINT

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This paper was prepared for submittal to
the Fifth Moriond Astrophysics Meeting
Les Arcs, France
March 17-23, 1985

May 1985

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__ABSTRACT__. We argue that the solar-system σN curve can be best understood if the s-process is largely produced by stars in the mass range of $M \sim 2\text{-}4\ M_{\odot}$. Several observations are then studied as indicators of the validity of this hypothesis. We find that isotopic Zr abundances and elemental (Ba/Sr) vs. (Ba/Nd) ratios are consistent with these conditions. The elemental (Tc/Nb) ratio is found not to be an indicator of temperature as has been suggested but rather a measure of the age of an AGB star in the third dredge-up phase.

1. INTRODUCTION

As we have already heard at this conference, the σN curve for solar-system material seems to imply s-process conditions of $n_n \sim 1.0(^{+0.2}_{-0.6})\times10^8\,\mathrm{cm}^{-3}$, $T = 0.30\pm0.04\times10^9$ K and $\tau_0 = 0.28 \pm .01\ \mathrm{mb}^{-1}$ corresponding to a thermal pulse duration of $\sim 500^{+300}_{-100}$ yrs (Mathews, _et al_. 1984ab; Howard, _et al_. 1985).

These parameters seem to be telling us something about the nature of the astrophysical site for the s-process. In particular, the empirically derived temperature is remarkably close (Almeida and Käppeler 1983) to the optimum temperature for a $^{22}Ne(\alpha,n)^{25}Mg$ neutron source, which operates in the thermally pulsing phase for AGB stars (Iben 1977) with core masses $> 1.0\ M_{\odot}$. On the other hand, the pulse duration, is more characteristic of AGB stars with lower mass cores. In this paper we make the point that this apparent contradiction can be resolved on the basis of more recent calculations (Becker 1985) which show that the temperatures for the full amplitude pulses for low-mass stars are sufficiently high ($T_9 \sim 0.3$) that the $^{22}Ne(\alpha,n)^{25}Mg$ source can be significant. Thus, a consistent argument can be constructed that the most likely site for the s-process is in the thermally-pulsing phase of relatively low-mass ($M \sim 2\text{-}4\ M_{\odot}$) AGB stars.

Since stars in this mass range also correspond to most observed S- and Ba stars, we next investigate the consistency of this interpretation with observed s-process abundances in these stars. In particular, we find that a measure of the neutron exposure can be obtained from the Sr/Ba elemental ratio, and an upper limit to the neutron density can be inferred from the Ba/Nd ratio. Isotopic abundances from ZrO lines (Zook 1978) can also be used to determine ranges of allowed values for n_n and τ_o. Both of these constraints are consistent with relatively low-mass AGB stars as the site for the s-process.

Finally, we briefly consider quantitative observations (Smith and Wallerstein 1983) of the Tc abundance on S-stars which have been suggested as a probe of the s-process temperature. We show that the Tc abundance is largely independent of temperature due to the fact that the neutron production is even more temperature sensitive than the ^{99}Tc beta half life. We then compute the expected Tc/Nb and Tc/Mo ratios and show that these quantities can be used as a measure of the lifetime of a star in the thermally pulsing third dredge-up phase.

2. IN SEARSH OF THE SITE FOR s-PROCESS NUCLEOSYNTHESIS

In a number of papers (Iben 1977; Truran and Iben 1977; Iben and Truran 1978; Cosner, Iben and Truran 1980) it has been argued that the s-process occurs in thermally pulsing AGB stars with relatively massive ($M_c \sim 1$-$1.4\ M_\odot$) electron-degenerate carbon-oxygen cores. This conclusion was reached on the basis of the fact that the $^{22}Ne(\alpha,n)^{25}Mg$ reaction seems to give the neutron exposure required to fit the solar-system σN curve.

The neutron densities corresponding to these core masses, however, are too high to give a satisfactory fit to the solar-system s-only nuclei. We have investigated two possible remedies to this dilemma. One is to postulate (Clayton 1984) a weak interpulse exposure ($\Delta\tau \sim .01 - 0.10\ mb^{-1}$) which is insignificant compared with the total exposure but which can heal the dips in the σN curve caused by the high neutron density. The problem we have found with this approach is that, by the time that enough exposure is introduced to heal the σN curve, branching at the low-temperature exposure leads to a poor fit to the σN curve.

The scenario which we prefer is based on the calculations of Becker (1981; 1985). These calculations show that, for the low-mass cores, the thermal pulses continue to heat up for about the first 20 pulses to a maximum temperature which is very close to the empirically derived temperature of $T_9 \sim 0.30$. For these temperature, the pulses endure long enough to provide sufficient neutron exposure without an excessively high neutron density. In calculating the exposure we have used the analytic relations of Iben and Truran (1978) and a constant peak temperature of $T_9 = 0.31$ for $M_c < 0.96\ M_\odot$. This is a reasonable approximation to the actual numerical output from the stellar models.

Figure 1 is an example of the reduced χ_r^2 for the fit as a function of core mass for these models with increased temperature. The fit is quite good for $M_c \sim 0.65\ M_\odot$, which is shown in Fig. 3. This initial core mass corresponds to roughly a $3\ M_\odot$ star (Iben

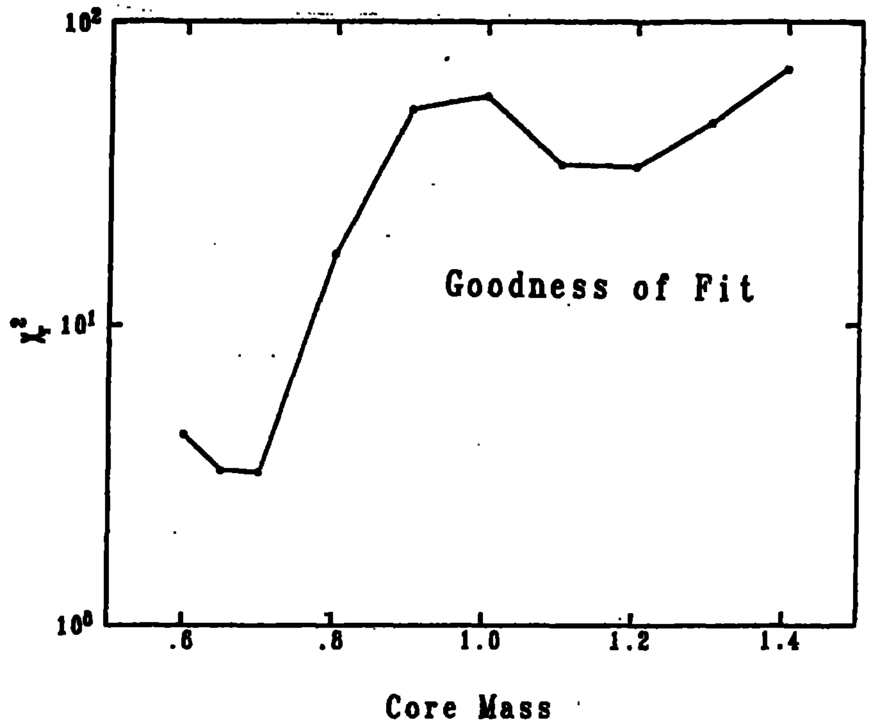

Fig. 1 Reduced $\chi_r{}^2$ for fit to solar-system σN curve as a function of core mass (units of $M_\odot$).

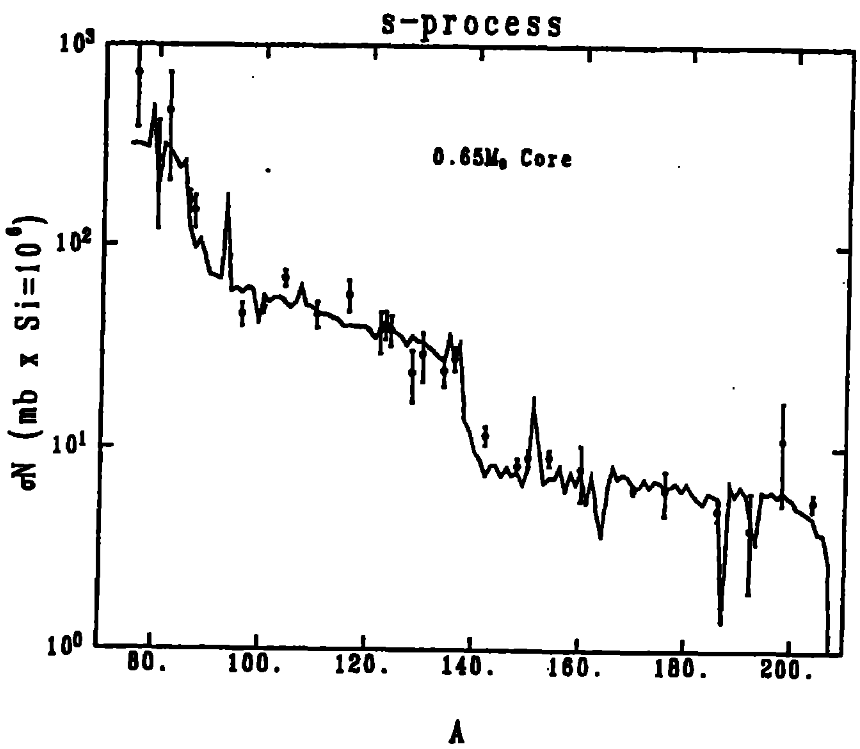

Fig. 2 Fit to solar-system σN curve for a star with a 0.65 $M_\odot$ carbon-oxygen core.

and Truran 1978). The implication is that the solar system s-process material has been largely produced by relatively low-mass AGB stars since the fit is significantly worse if an average over the entire mass range is used.

This is consistent with the suggestion (Scalo and Miller 1981) that the third dredge-up may not occur in the higher-mass stars and the lack of observation of Tc lines in AGB stars with $M \gtrsim 3\ M_\odot$.

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This leads us to suggest that it would be useful to consider observations of s-process abundances in low-mass AGB stars to see if these data are consistent with the implications from the solar system σN curve. It would, of course, be most useful to have good isotopic abundance measurements. Unfortunately these are not available for most elements. However, Zook (1978) has obtained isotopic Zr abundances from ZrO lines in three S-stars. These data are shown in Fig. 3 along with calculated Zr isotopic abundances as a function of core mass. As can be seen, the best fit is for the low core masses.

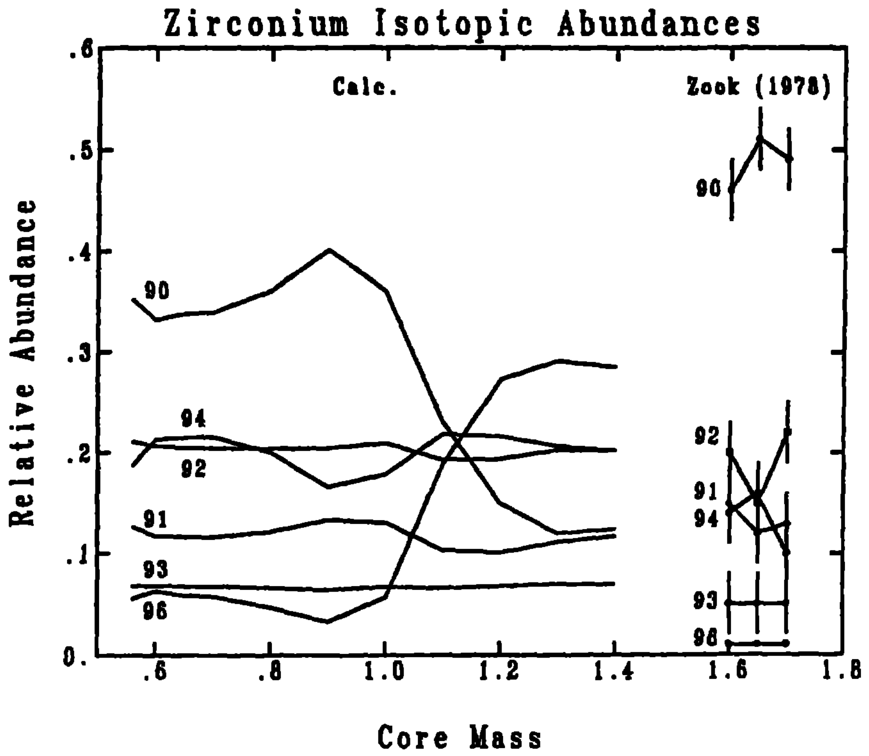

Fig. 3 Relative Zr isotopic abundances calculated for stellar models. The data are from the observations of Zook (1978).

What about elemental abundances? From variation of neutron exposure at a constant neutron density, we find that there is a dramatic variation of a stepwise behavior of the elemental abundances. From this study it appears that the Sr/Ba ratio is a good indicator of neutron exposure. Variation of the neutron-density over 11 orders of magnitude for a fixed exposure produces little change in the relative abundances. In particular, the Ba/Sr is invariant to a good approximation. This elemental ratio is, therefore, a good measure of the neutron exposure.

There is, however, one significant change. The Nd abundance decreases by about a factor of two. The reason for this is that the Nd abundance is normally dominated by the s-only isotope, ^{142}Nd. For neutron densities $n_n \geq 10^9$ cm^{-3}, however, ^{142}Nd is bypassed due to neutron captures on the unstable isotope, ^{141}Ce. Thus, the Ba/Nd ratio is a measure of the neutron density when the $n_n > 10^9$ cm^{-3}.

Figure 4 shows predicted behaviors for the Sr/Ba and Ba/Nd ratios as a function of neutron density and neutron exposure. The observations (Cowley and Downs 1980) for several of Ba stars are also indicated. Although the uncertainties are large, it is clear that, at least for the stars indicated, the densities and exposures tend to be consistent with the low neutron densities associated with lower core masses.

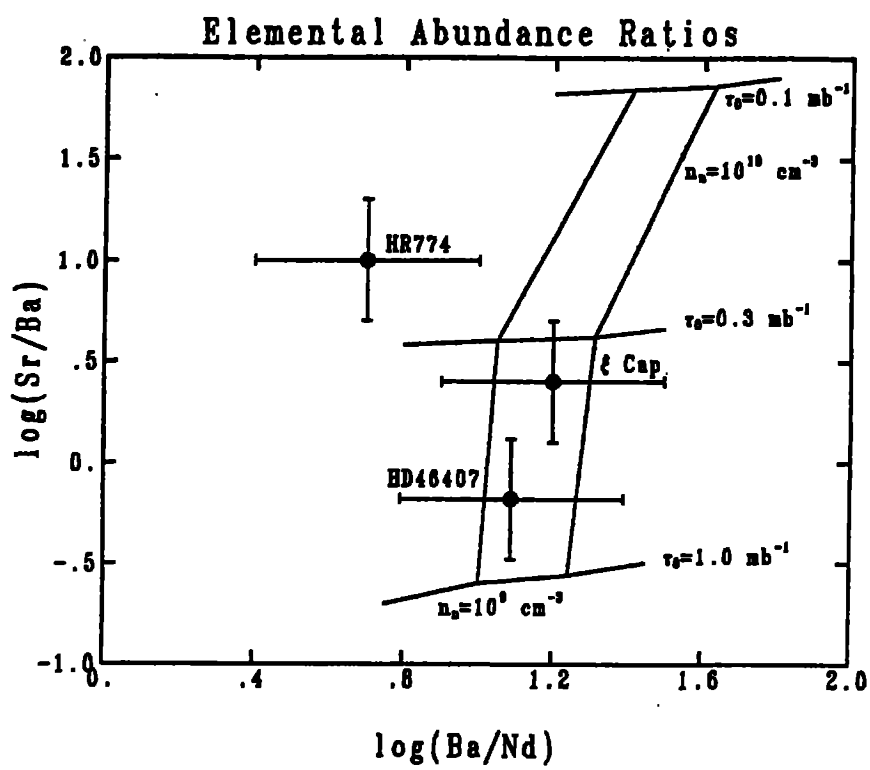

Fig. 4 Correlation of (Sr/Ba) and (Ba/Nd) elemental ratios. Lines correspond to constant neutron density and exposure. The data are from Cowley and Downs (1980).

4. TECHNETIUM ABUNDANCES

Another possible probe of the stellar environment is suggested by the quantitative observations of unstable Tc (probably ^{99}Tc) on stellar surfaces (Smith and Wallerstein 1983). Because the beta-decay halflife for ^{99}Tc is expected (Cosner, Despain and Truran 1984) to be drastically diminished at stellar temperatures ($\tau_{1/2} \sim 1$ yr. rather than $\tau_{1/2} \sim 2.1 \times 0^5$ yr. terrestrially), it has been suggested that Tc abundances on stellar surfaces may indicate low-temperatures for nucleosynthesis. We find (Mathews et al. 1985), however, on the basis of our detailed network calculations, that a significant fraction of the Tc abundance (70-90%) survives to the end of the convective shell, almost independent of core mass in these models. The reason is simply that the abundance of ^{99}Tc is determined by both the beta-decay rate and its neutron capture rate. Because the capture cross section for ^{99}Tc is so large (854 mb (Macklin 1984)), and the ^{22}Ne(α,n)^{25}Mg, neutron source increases so rapidly with temperature, the σN value for ^{99}Tc is very close to the value it would have if there were no beta decay.

Since the ^{99}Tc abundance is not particularly temperature sensitive, it is useful to see what the observations (Smith and Wallerstein 1983) are telling us about the stars producing ^{99}Tc. Figure 5, (from Mathews et al. (1985)) shows the predicted (Tc/Nb) and (Tc/Mo) ratios as a function of the lifetime of a star in the thermally pulsing third dredge-up phase. This figure is based on a simple analytical two-reservoir model (Anders 1958; Peterson and Wrubel 1966). The points are two S-stars measured by Smith and Wallerstein

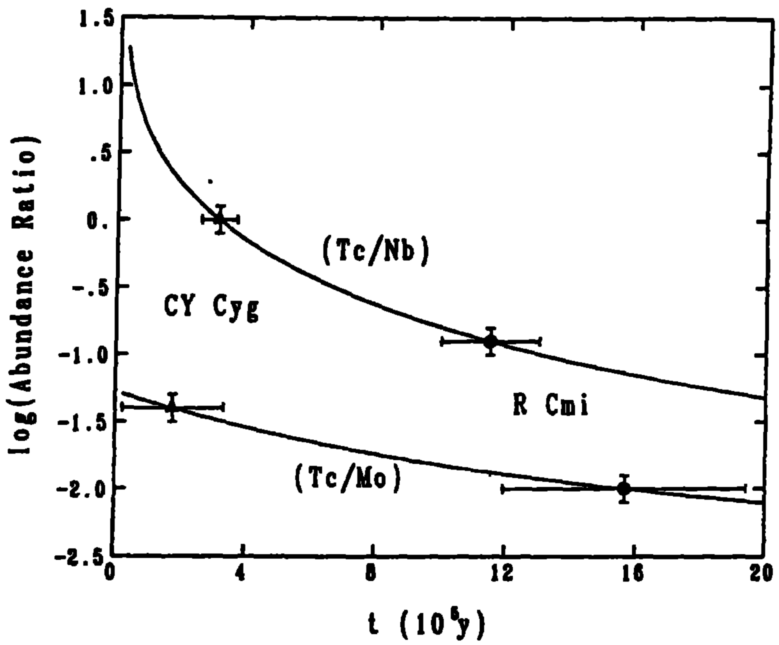

Fig. 5 Predicted behavior of the surface (Tc/Nb) and (Tc/Mo) ratios as a function of the age of an AGB star in the thermally-pulsing third dredge-up phase.

(1983). From this figure it can be seen that this approach can be used to give a good indication of the age of a star in this phase of evolution.

5. CONCLUSION

The basic conclusion of this work is that, from a number of different ways of looking at the problem, the thermally-pulsing phase of AGB stars in the mass range of 2-4 $M_\odot$ appears to the most promising site for the s-process. We suggest that it will be useful for further study to compile Zr isotopic abundances as well as (Sr/Ba), (Ba/Nd), and (Tc/Nb) elemental ratios for a number of stars as a best means to test this hypothesis.

6. ACKNOWLEDGEMENT

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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